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RESEARCH DEPARTMENT

Stereophony: the effect of crosstalk between left and right channels

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THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

STEREOPHONY:
THE EFFECT OF CROSSTALK BETWEEN LEFT AND RIGHT CHANNELS

Research Report No. L-049/2

(1964/1)

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Section	Title	Page
	SUMMARY	1
1.	INTRODUCTION	1
2.	EXPERIMENTAL DETAILS	2
	2.1. General	2
	2.2. Position of Observer	3
	2.3. Crosstalk increasing at High Frequencies	3
	2.4. Crosstalk increasing at Low Frequencies	4
	2.5. Crosstalk Independent of Frequency	4
	2.6. Programme Loudness	4
	2.7. Presentation of Test Material	4
3.	RESULTS	5
	3.1. Observer in Central Position	5
	3.2. Observer in Off-Centre Position	10
	3.3. Crosstalk as Function of Frequency	12
	3.4. Spread of Results	14
	3.5. Lateral bias of Observers	15
4.	COMPARISON WITH EARLIER WORK	16
5.	CONCLUSIONS	19
6.	REFERENCES	19

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SUMMARY

The investigation of the effect of interchannel crosstalk in a stereophonic system, of which the first results were given in Research Report L-049, has been continued. The experiments have covered crosstalk in different regions of the audio-frequency band. The influence of acoustic environment and of the observer's position in relation to the loudspeakers has been investigated, as well as the effect of restricting the frequency range of the programme. Comparisons are made with published work.

1. INTRODUCTION

One of the technical defects which may appear in a stereophonic sound system is the unintentional transference of a portion of the signal in one of the channels to the other channel. To describe this phenomenon, which in stereophony can produce a displacement or blurring of the acoustic images, it is usual to borrow from the vocabulary of the telephone engineer the term 'crosstalk'. This crosstalk can arise from a variety of causes, and presents a particularly serious problem in disk recording; of particular interest for the present purpose, however, is the crosstalk which may appear in a stereophonic broadcast transmission system.

In an earlier report[1] an account was given of experiments to determine subjectively the effect, on a stereophonic image, of crosstalk between left- and right-hand channels. These tests, carried out in the A.F. Section listening room, were confined to crosstalk increasing with frequency at the rate of 6 dB/octave, a condition which may occur in multiplex transmission systems. The present report describes two further series of experiments on the subjective effect of crosstalk. In the first of these, the original tests were repeated under different listening conditions, and the effect of restricting the frequency range of the programme material, which in the earlier tests extended to 13 kc/s, was also investigated. In the second, similar methods were employed to determine the effect of crosstalk increasing progressively at low frequencies, and of crosstalk independent of frequency; both conditions can occur in multiplex systems - the former through faulty design and the latter through faulty adjustment.

2. EXPERIMENTAL DETAILS

2.1. General

The listening room and equipment, the layout of which is shown in Fig. 1, were the same as in the original crosstalk experiments,[1] and the same twelve observers took part in the tests.

The two loudspeakers employed were well matched. Over the range 3 kc/s to 13 kc/s and 40 c/s to 250 c/s, which contain most of the components of interest in the experiments on crosstalk increasing at high and low frequencies respectively, the axial frequency characteristics lay within ± ½ dB of one another; within the middle frequency band (250 c/s to 3 kc/s), the differences were less than ± 1 dB except in the crossover region (800 c/s to 1600 c/s), where local deviations up to ± 2 dB existed. To minimize the effects of residual asymmetry of the loudspeaker system, of the acoustic environment and of the observer's directional sense, all tests were repeated with the programme and crosstalk channels interchanged, the two results being subsequently averaged.

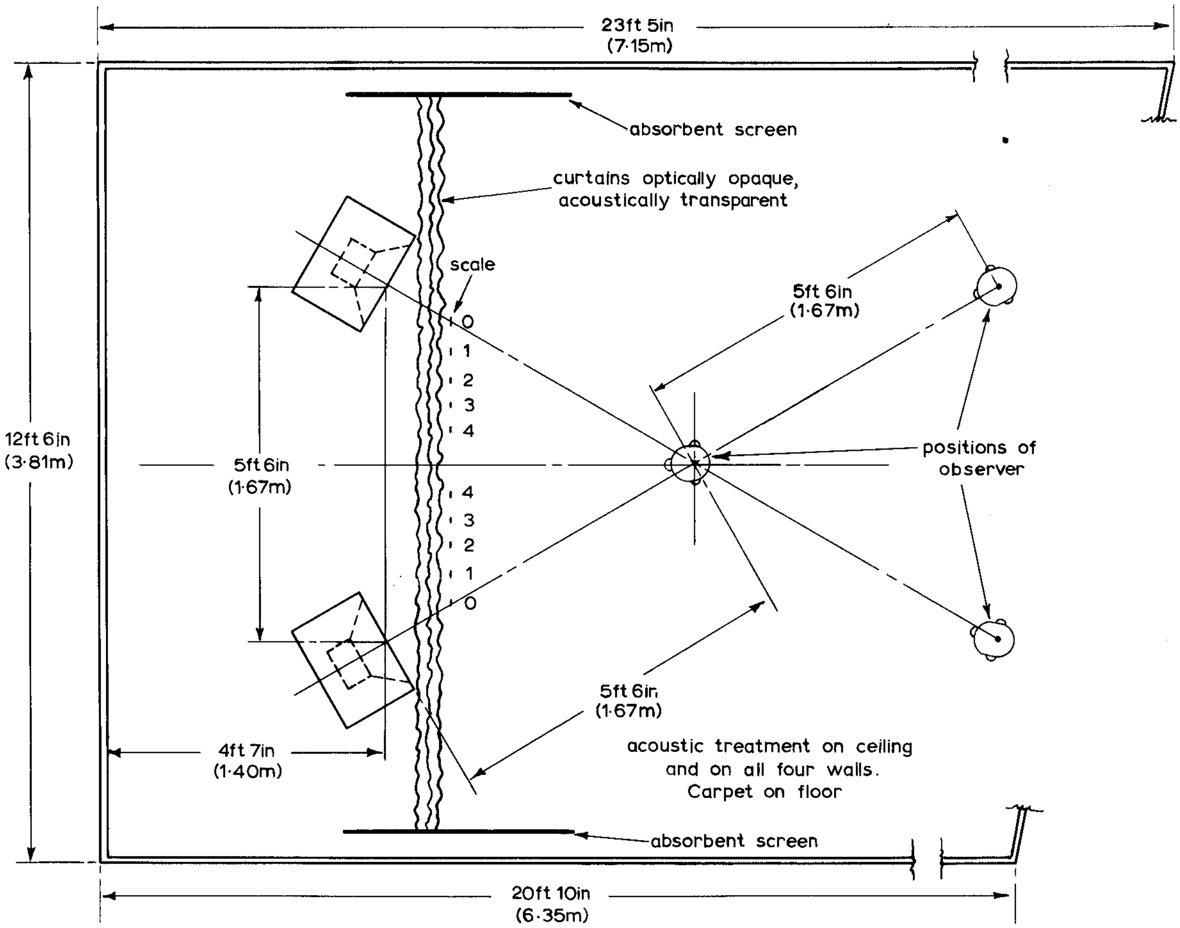

Fig. 1 - Plan of Listening Room

To discover how far the subjective effect of crosstalk depends on the acoustic environment, most of the experiments were repeated in a dead room, normally employed for measurements on microphones and loudspeakers, in which the reflexion coefficient of the walls at frequencies above 80 c/s was less than 10%. These dead surroundings represent an extreme acoustic condition and have the advantage that they can be duplicated in other laboratories.

2.2. Position of Observer

Most of the experiments were carried out with the observer in the central position. It was thought, however, that if the listening position were located nearer to the loudspeaker reproducing the crosstalk and further from that reproducing the programme, the alteration in the relative levels, coupled with the precedence effect, would make the result of the crosstalk more noticeable. The more critical tests were therefore repeated with the observer placed, as shown in Fig. 1, in a position to one side of a hypothetical triangular seating layout and facing towards the centre of the stage.

2.3. Crosstalk increasing at High Frequencies

In these experiments the method of introducing the crosstalk was similar to that adopted in the earlier tests, the signal from one channel reaching the other being proportional to frequency and leading 90° in phase; the same test passage - an excerpt from a recording of Latin American music - was also used. The bandwidth was, however, restricted in some of the tests to a nominal upper limit of 6 kc/s or 10 kc/s by low-pass filters having the frequency response shown in Fig. 2(a); the rate of

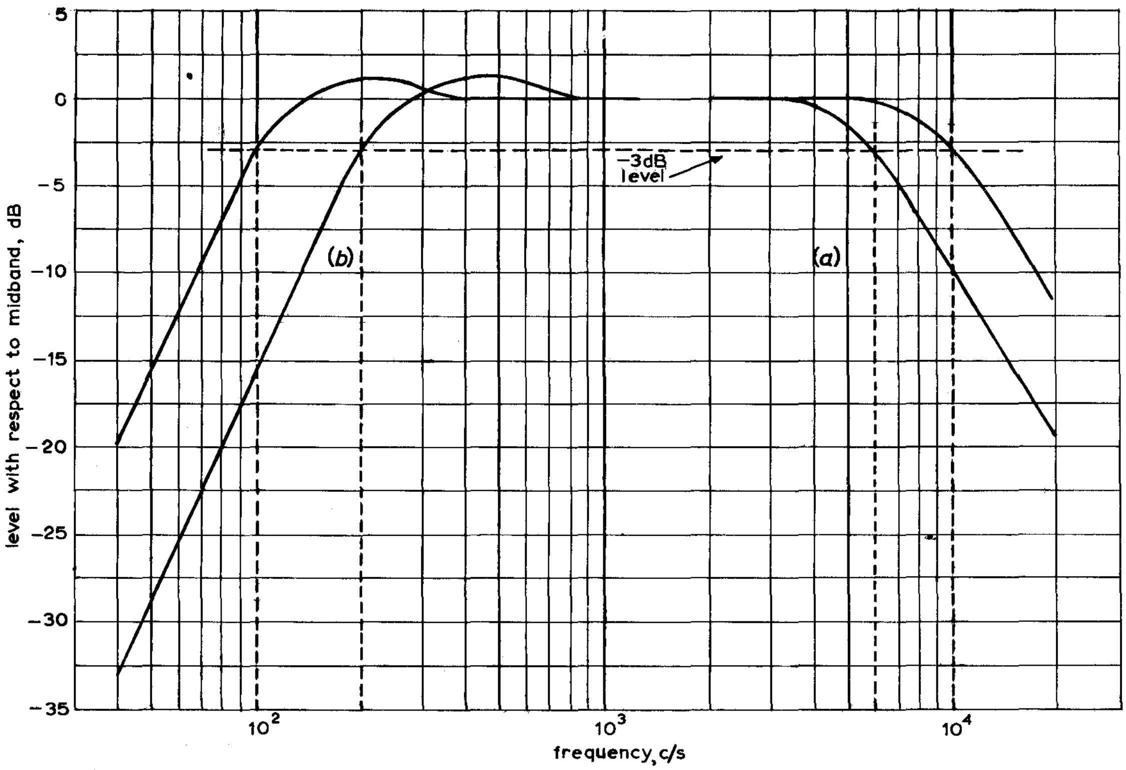

Fig. 2 - Frequency response of filters used for limiting programme bandwidth
(a) Low Pass (b) High Pass

cut-off was deliberately restricted to 12 dB/octave to avoid ringing at the cut-off frequency. The nominal limit of the band was taken as the frequency at which the filter attenuation exceeded the mid-band value by 3 dB. The filters were inserted in the common signal channel and did not therefore introduce any additional phase difference between the programme and crosstalk. In the absence of the filters, the upper frequency range of the programme material was restricted to 13 kc/s by the characteristics of the loudspeakers used and this condition will therefore be referred to for convenience as the 13 kc/s limit.

2.4. Crosstalk increasing at Low Frequencies

For these experiments, the test circuit was modified so that the signal from one channel reaching the other was inversely proportional to frequency and lagging 90° in phase. As in the earlier experiments, no attempt was made to compensate for phase shift, since this would normally appear in practice. The programme material consisted of separate recordings of organ, bass drum and plucked double-bass; the spectrum extended down to 40 c/s in each case, and this figure will therefore be used for convenience in referring to the lower limit of the unrestricted frequency range.

Fig. 2(b) shows the frequency characteristics of the filters, in this case of the high-pass type, employed in some of the tests to restrict the low-frequency range of the programme.

2.5. Crosstalk Independent of Frequency

For the experiments with crosstalk independent of frequency the programme material employed consisted of male speech, and no attempt was made to restrict the frequency range. Since the spectrum of speech contains no strong components at the extremes of the audio-frequency band, this test is principally representative of the middle of the band; the resulting data can therefore be combined with that obtained with crosstalk increasing at high and low frequencies respectively, to produce tolerance figures for the whole audio-frequency range.

The crosstalk signal was transferred from one channel to the other without change of phase.

2.6. Programme Loudness

As in the previous experiments, the maximum sound level for most of the tests was set at 74 dB on an unweighted sound-level meter, the preferred listening level for the general public.[2] A few additional tests were carried out on crosstalk at low frequencies for levels 6 dB above and below this figure; the effect of such level changes on the results was no greater than that already found[1] with crosstalk at high frequencies.

2.7. Presentation of Test Material

The degree of crosstalk was controlled by the observer, who was asked to adjust an attenuator until the position of the inner edge of the image coincided with one of the divisions on the scale shown in Fig. 1. At a later stage in each test, the observer was asked to find the setting of the attenuator corresponding to the minimum perceptible displacement of the edge of the image from its position with no crosstalk. It was necessary to avoid the possibility of an observer's decision

in one test being affected by his recollection of the setting obtained in another; the experimenter was therefore provided with a preset attenuator connected in tandem with that controlled by the observer, the amount of additional attenuation thereby introduced being varied between tests.

3. RESULTS

3.1. Observer in Central Position

Figs. 3 and 4 show the relationship between crosstalk and image displacement

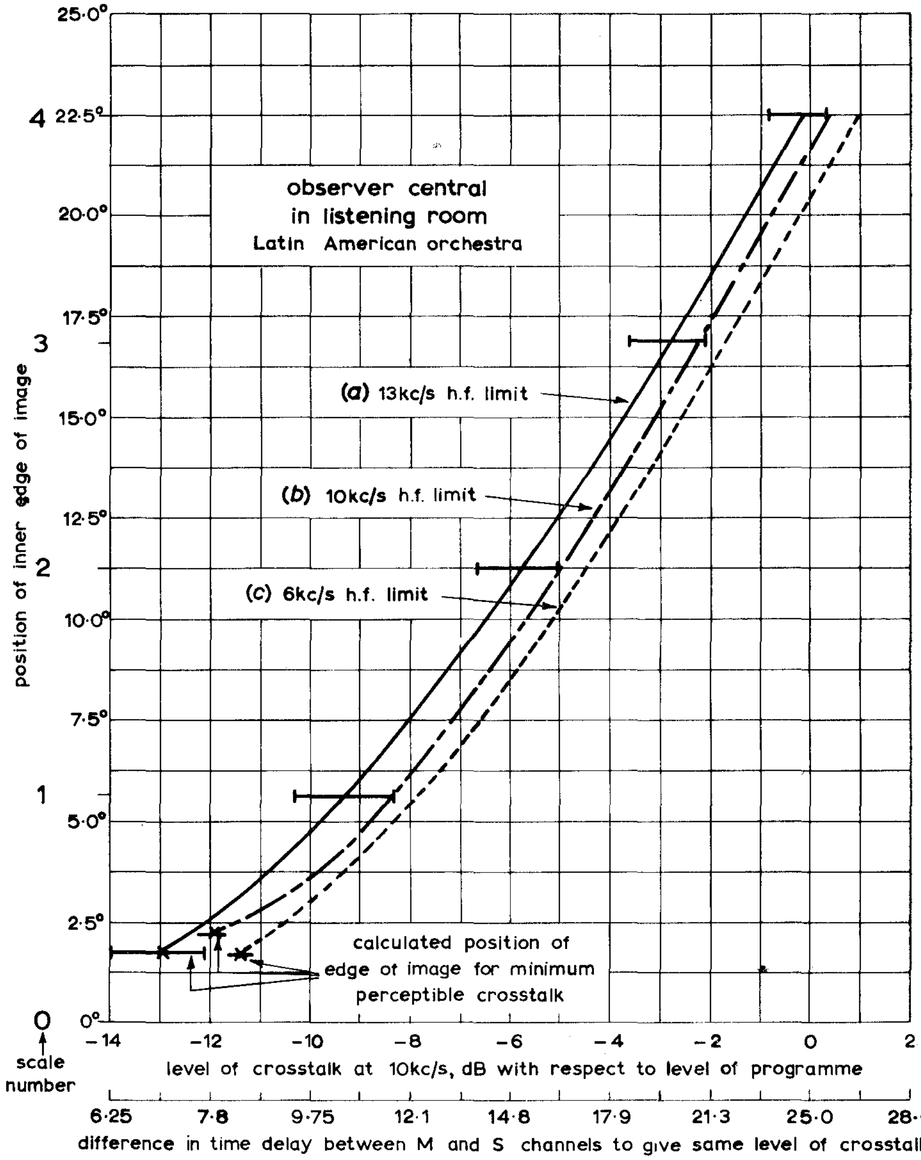

Fig. 3 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer central in Listening Room

Standard error shown thus ⊢—⊣

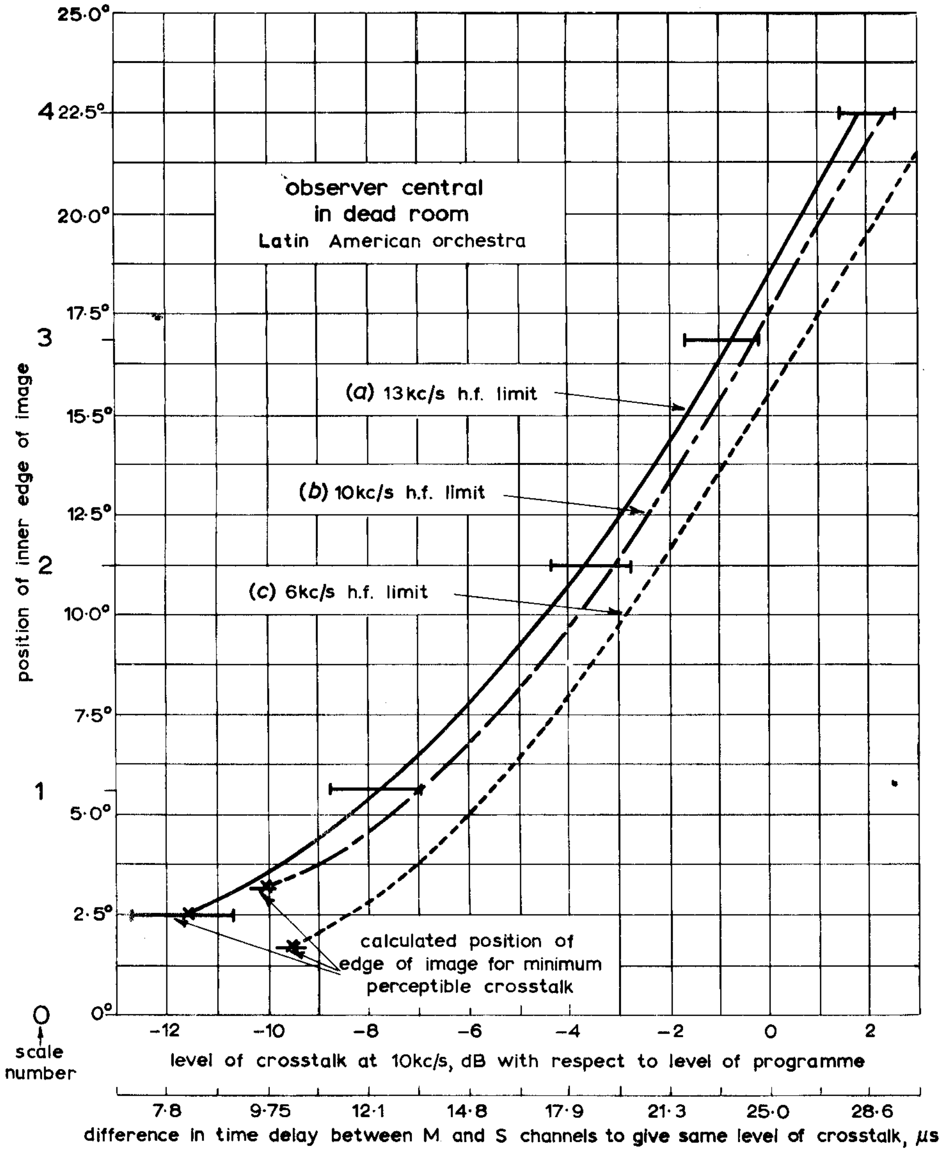

Fig. 4 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer central in Dead Room

Standard error shown thus

for observers in the listening room and dead room respectively for crosstalk increasing at high frequencies; curves (a), (b) and (c) are for the three different bandwidths. As in the earlier experiments, the crosstalk is specified by its level, with respect to the level of the programme, at 10 kc/s, and a supplementary scale is provided to show the degree of time displacement between the sum and difference channels (usually known as the M and S channels respectively) of a multiplex transmission system[1] which would produce the same effect. The results represent the mean of all the observations; to indicate the order of experimental accuracy involved, the standard error is shown, but for the sake of clarity this is in general marked on one curve only. Figs. 5 and 6 show the corresponding results for crosstalk increasing at

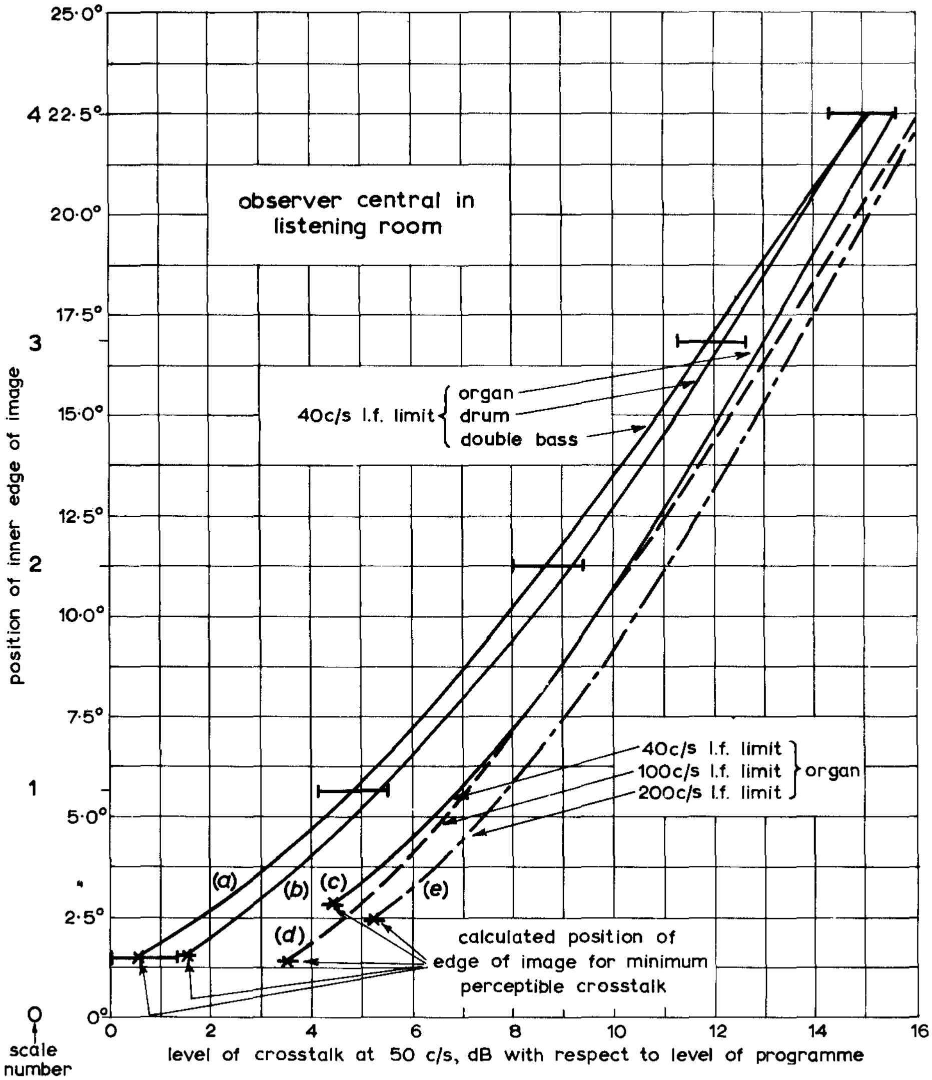

Fig. 5 - Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer central in Listening Room

Standard error shown thus ├──┤

low frequencies, the level of crosstalk with reference to programme being taken for reference purposes at 50 c/s; the experiments with restricted bandwidth were confined to organ music. In each case the position assigned to the inner edge of the image for the minimum perceptible value of crosstalk was estimated, as explained in the earlier report,[1] from the probable error of the data from individual observers; the figure thus obtained is not very different from that which would have been arrived at by extrapolation of the curve.

Some of these curves extend into the region of positive abscissae, in which the level of crosstalk produced by a signal at 10 kc/s or 50 c/s respectively is greater than that of the programme. This condition could easily occur in a multiplex transmission system[1] at high frequencies on account of differences in time delay between the sum and difference channels; at low frequencies such a situation is less

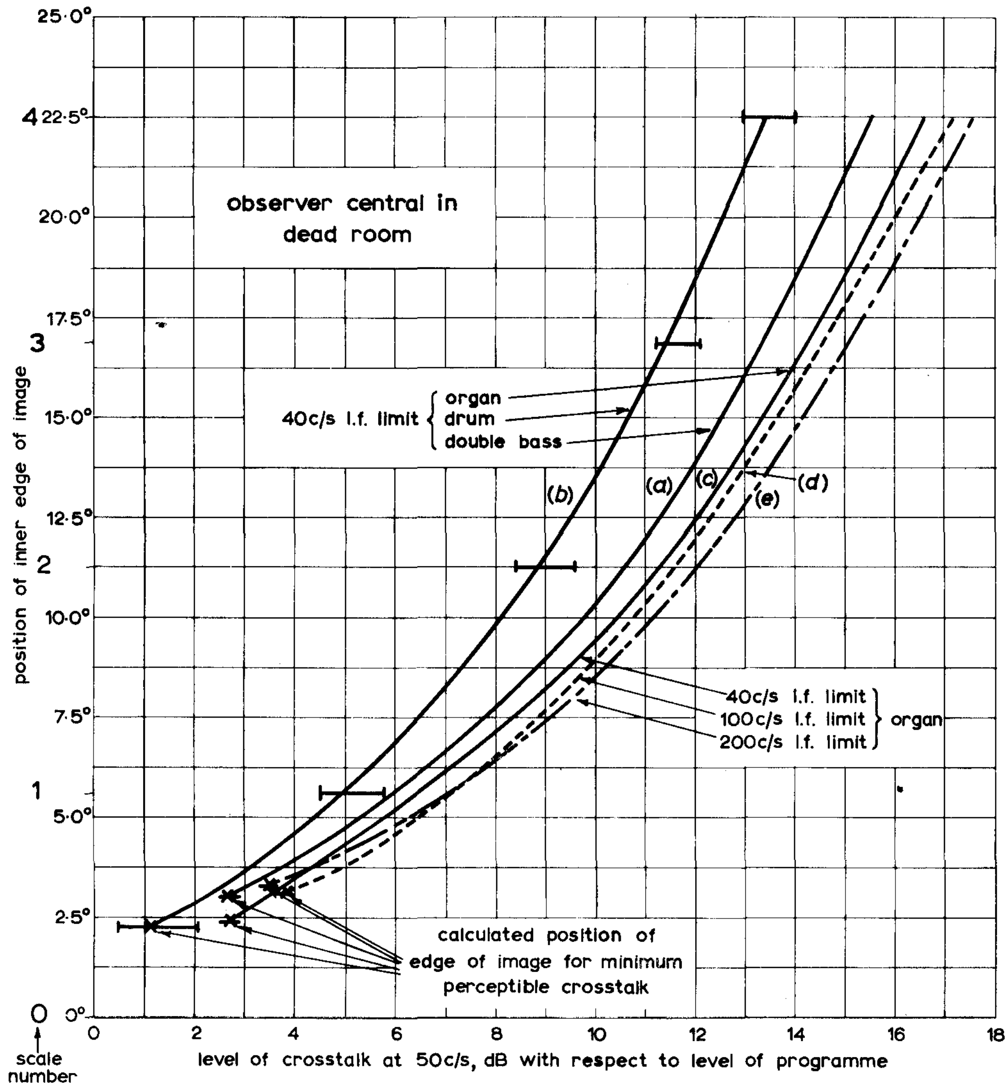

Fig. 6.-Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer central in Dead Room

Standard error shown thus ⊢—⊣

likely, but could arise if a high-pass filter were used to restrict the bandwidth of the difference channel.

It will be observed in Figs. 3 to 6 that the subjective effect of crosstalk is only slightly reduced by restricting the frequency range of the programme. This result was confirmed by an independent experiment in the listening room for the case of crosstalk increasing at high frequencies; each observer was asked to set the inner edge of the image to division 4 on the scale for the 13 kc/s frequency range and to note the change in position of the edge when the high frequency range was suddenly restricted to 6 kc/s by switching in the appropriate filter. Although the change in tonal quality was very marked, the image displacement was found to be small and in the direction indicated by the curves. That restriction of the frequency band should have so little effect suggests that components of the sound lying well inside the

audio-frequency band may tend to obscure the position of those at the extremes of the frequency range. It would not, however, be safe to assume that further restriction of the programme bandwidth would have no effect on the image displacement.

Comparing Fig. 4 with Fig. 3, it will be seen that for the 13 kc/s and 10 kc/s frequency range, the results obtained with crosstalk near to the minimum perceptible level were not significantly affected by the change in acoustic environment; at higher levels of crosstalk and with the frequency range restricted to 6 kc/s, the image displacements observed were only slightly less in dead surroundings. Similarly, comparison between Figs. 5 and 6 shows that the change in acoustic environment had no great effect on the perceptibility of crosstalk at low frequencies.

Fig. 7 shows the image displacement produced in the listening room by crosstalk independent of frequency, with male speech as the programme material.

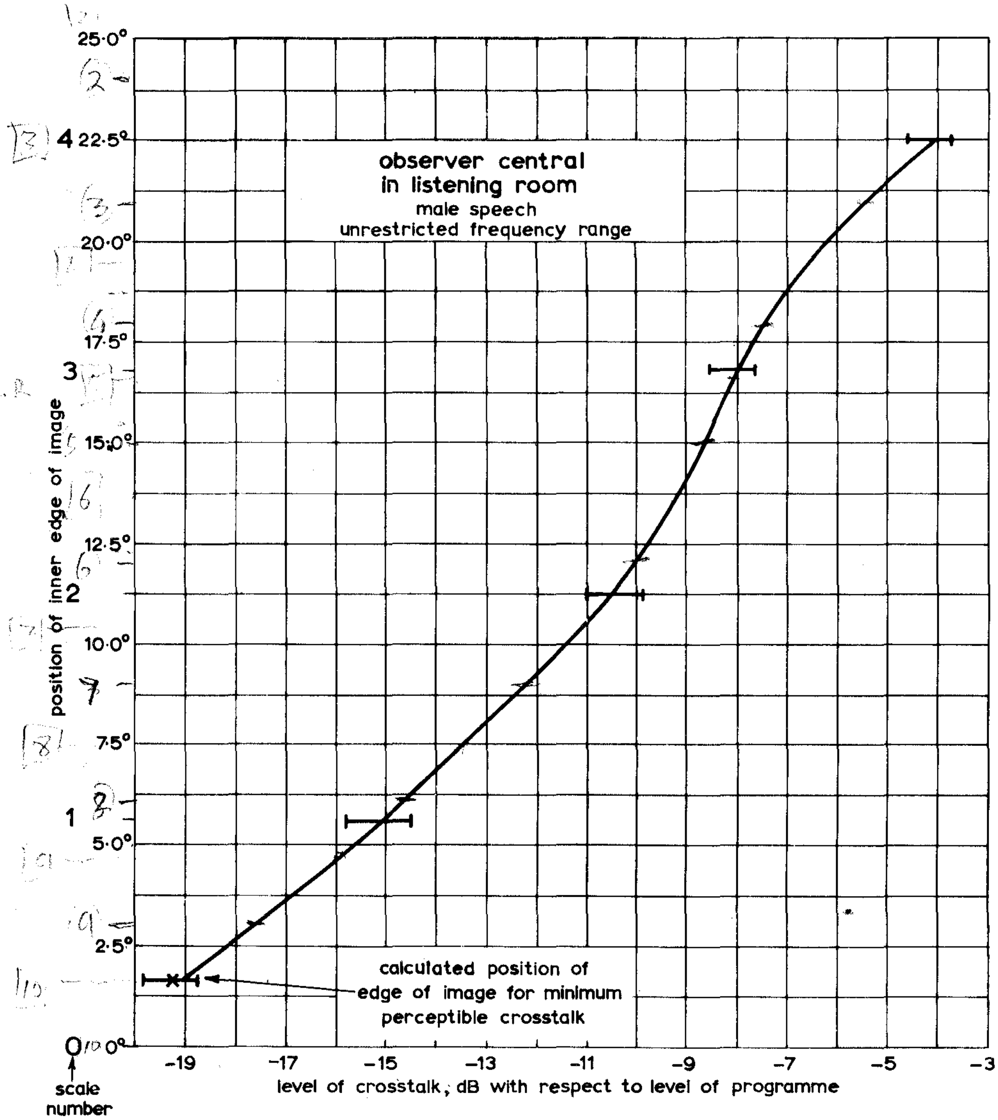

Fig. 7 - Position of inner edge of image as a function of crosstalk independent of frequency. Observer central in Listening Room

Standard error shown thus

3.2. Observer in Off-Centre Position

Figs. 8 and 9 show the relationship between crosstalk and image displacement with crosstalk increasing at high and low frequencies respectively, for an observer in the off-centre positions shown in Fig. 1. In these tests the full frequency range of the system was employed; for the case of crosstalk increasing at low frequencies, only the double-bass recording was used. Fig. 10 shows the corresponding results for male speech with crosstalk independent of frequency. In Figs. 8, 9 and 10, curve (a) in each case refers to the listening room and curve (b) to the dead room.

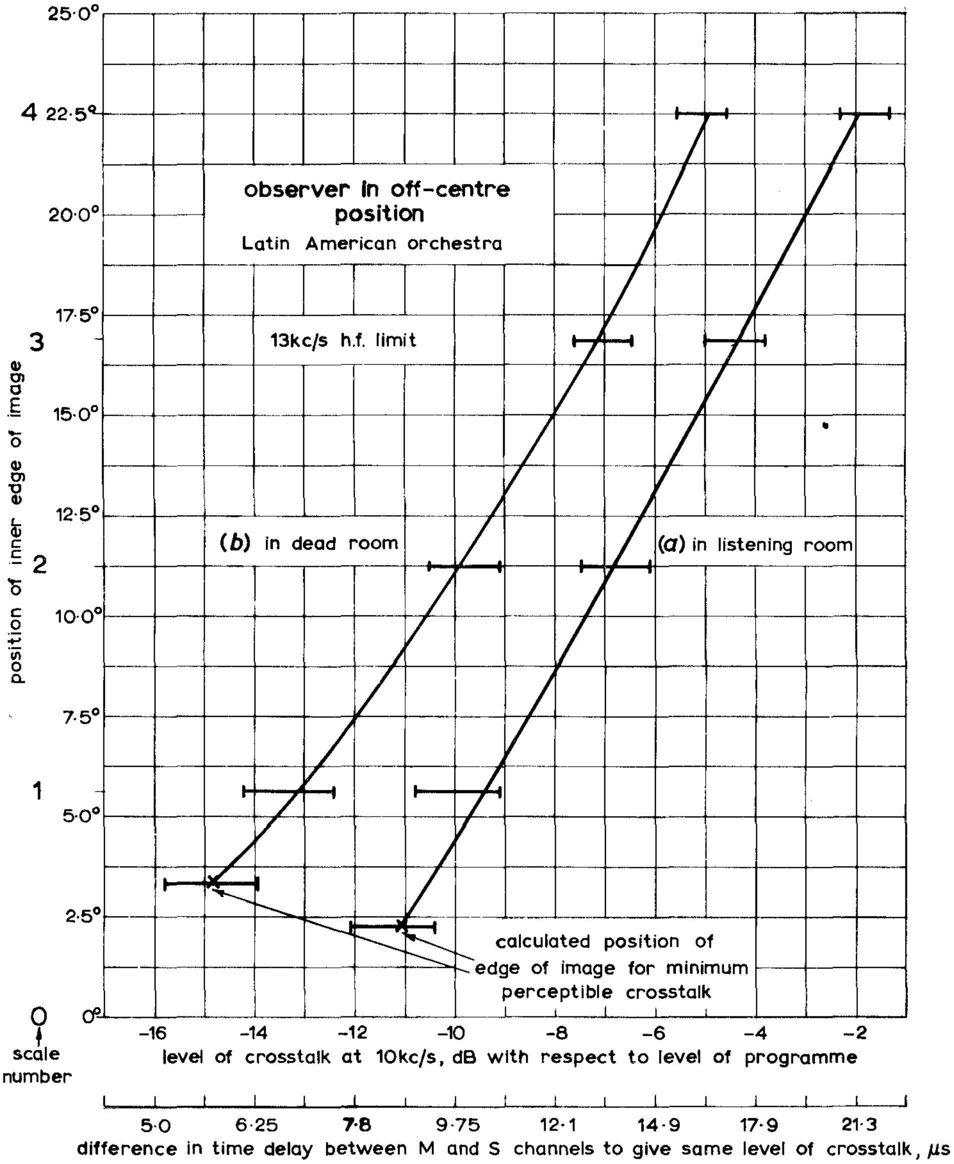

Fig. 8 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer off-centre in Listening Room and Dead Room

Standard error shown thus

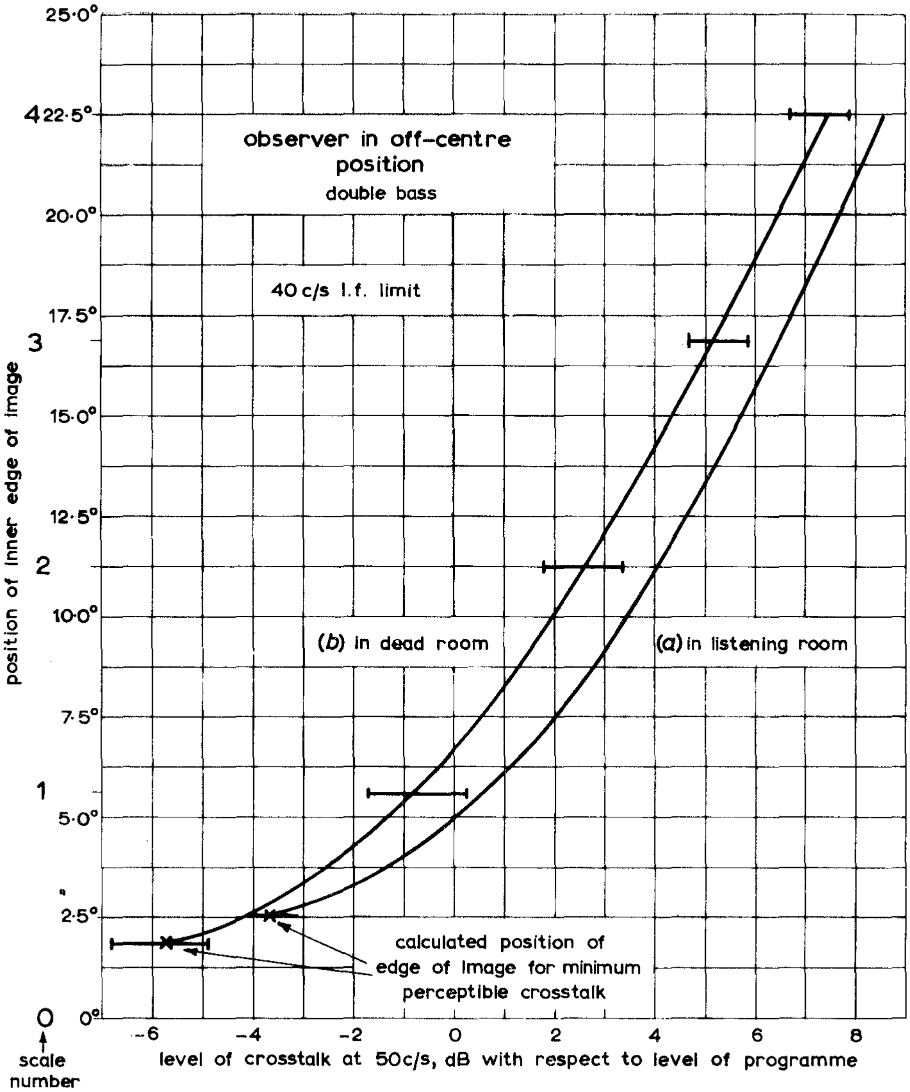

Fig. 9 - Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer off-centre in Listening Room and Dead Room

Standard error shown thus ⊢—⊣

By comparing these data with the corresponding results already given for the central position, it will be seen that the effect of moving the observer to the off-centre position depended on the part of the frequency range concerned. In the listening room the minimum perceptible level of crosstalk increasing at low frequencies was lowered by 4 dB. For crosstalk increasing at high frequencies and crosstalk independent of frequency, the figure was raised 2 dB; however, as the standard error in the measurements was about 2 dB, the change was hardly statistically significant.

In the dead room, the minimum perceptible level of crosstalk increasing at high frequencies was 3 dB lower for the off-centre position than for the central position; for crosstalk increasing at low frequencies the figure obtained in the off-centre position was lower by 7 dB; in both cases, the change was in the direction to be expected.

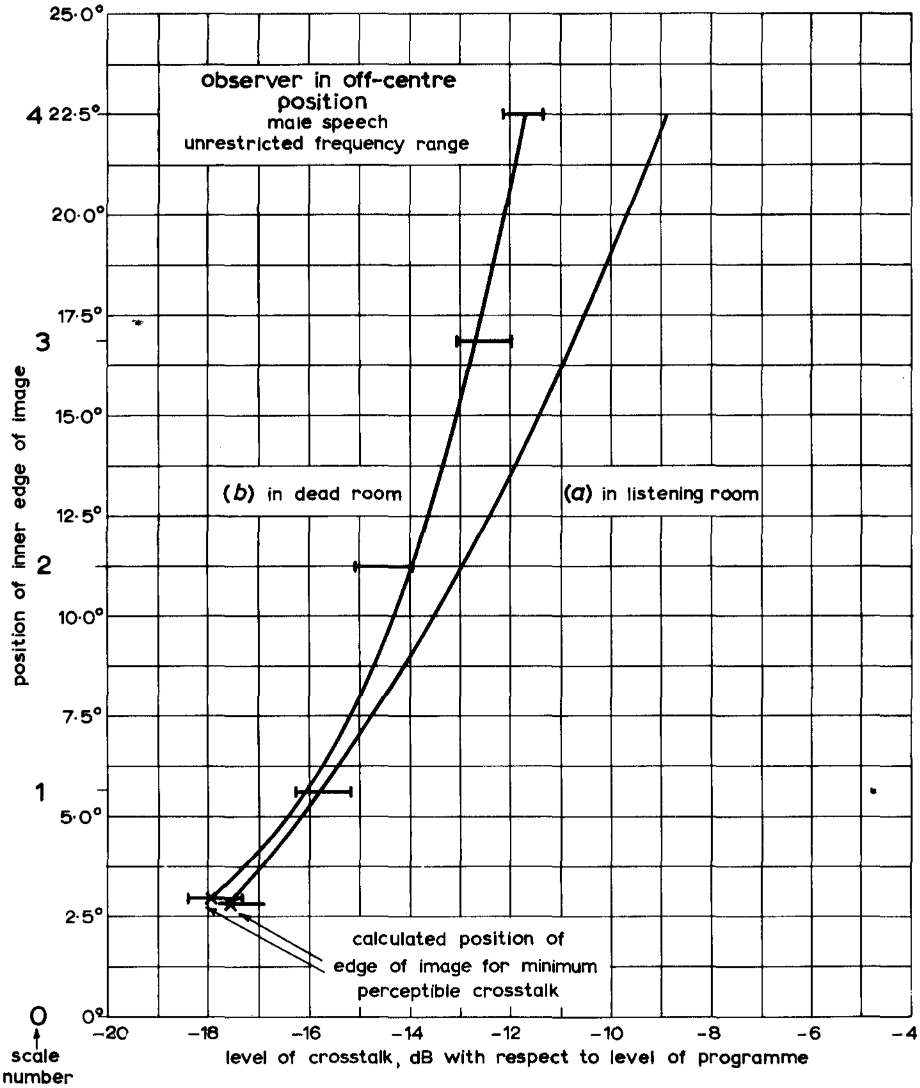

Fig. 10 - Position of inner edge of image as a function of crosstalk independent of frequency. Observer off-centre in Listening Room and Dead Room

Standard error shown thus

3.3. Crosstalk as Function of Frequency

Fig. 11 shows the crosstalk/frequency relationship existing in the test circuit when the subjective effect of the crosstalk was just perceptible. Most of the data relate to a central observer but corresponding curves for the off-centre position are also shown for cases in which the results were significantly different. All curves refer to the unrestricted frequency range 40 c/s to 13 kc/s; as already shown in Section 3.1. restriction of the frequency band by an octave at high frequencies and two and a half octaves at low frequencies has only a slight influence on the subjective result. Curve (a) relates to crosstalk rising 6 dB/octave at high frequencies. Curves (b_1) and (b_2) give the corresponding characteristics for crosstalk rising 6 dB/octave at low frequencies, taking the most critical type of programme

material in each case; curve (b_1) is for a central observer and curve (b_2) for an observer in the off-centre position. Fig. 11(a), (b_1) and (b_2) all apply, with sufficient accuracy, to both listening room and dead room, as the differences between the results in these two conditions are not statistically significant. The horizontal straight line (c) refers to the tests in the listening room on crosstalk independent of frequency. It must be emphasized that these curves give the characteristics of a system in which the effect of crosstalk is just perceptible on programme; they should not be taken to represent the minimum perceptible crosstalk for any one frequency considered separately.

In comparing curve 11(c) with curves 11(a), (b_1) and (b_2), the effect of the different phase relationships between crosstalk and programme has to be borne in mind. The 90° phase lead associated with the crosstalk increasing at high frequencies may for the purpose of this comparison be ignored, since in the region above 3 kc/s, the image position is determined by differences in time of arrival, rather than differences in phase,[3] between the signals applied to the two loudspeakers. On the other hand, at middle and low frequencies, the image position is a function of the relative phases of the signals applied to the two loudspeakers. Thus, in the particular case where the signal in one channel consists of crosstalk coming from the programme in the other channel, the phase relationship between crosstalk and programme must influence the subjective effect. For this reason, the 90° phase lag associated with the increase of crosstalk at low frequencies prevents direct comparison with the

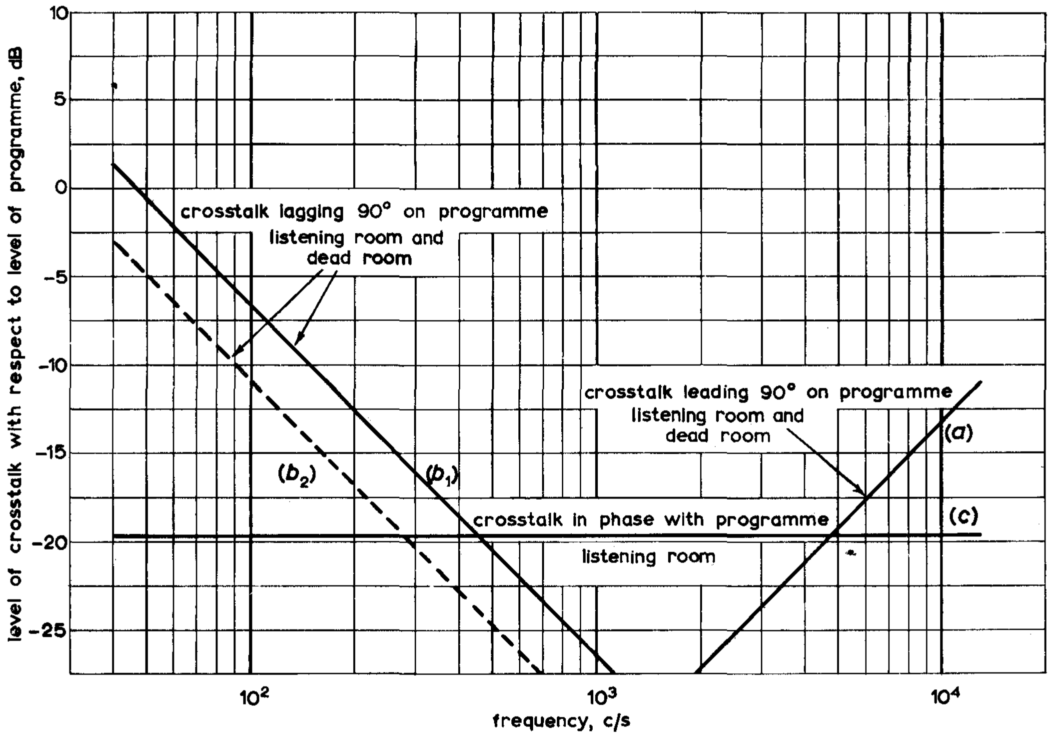

Fig. 11 - Crosstalk/frequency characteristic of test circuit for minimum perceptible subjective effect (mean of all observations). Frequency range 40 c/s to 13 kc/s

——— Observer central
- - - - Observer in off-centre position (see Fig. 1)

data on crosstalk independent of frequency, for which there is no phase shift. With this reservation, Fig. 11 can be taken as a rough overall picture of the kind of tolerances which might be imposed on a stereophonic system where the crosstalk increases gradually towards the extremes of the frequency band.

3.4. Spread of Results

The data presented in Figs. 3 to 11 relate to the mean of all the values given by the team of observers; thus, in 50% of the observations, a lower level of crosstalk than that shown as 'minimum perceptible' was detectable while in the remaining 50% a higher level went undetected. It is, however, of interest to consider the variation of opinions within the team. Fig. 12, which applies to the minimum perceptible crosstalk for a central observer in the listening room with unrestricted frequency range, shows the statistical distributions for the three cases: (a) crosstalk increasing at high frequencies, (b) crosstalk increasing at low frequencies and (c) crosstalk independent of frequency. The smallest divergence of opinion appears in case (c) in which, as already noted, the programme material contains no very strong components at the extremes of the frequency range. From Fig. 13, in which the same data are replotted on a Gaussian probability scale, the minimum crosstalk detectable by any percentage of the observers can be determined.

In addition to the variation of opinion between different observers, it is also of interest to know the degree of consistency with which each observer can repeat his performance under the same conditions. As indicated in Section 3.1., the average of the probable errors of the individual observer, expressed in terms of equivalent angular displacement across the stage, has been taken as a measure of the observer's acuity and also of the minimum perceptible image displacement. One such figure has been derived for each of the experiments described in Sections 2.4. and 2.5. and the collected results for the dead room and listening room tests respectively are plotted

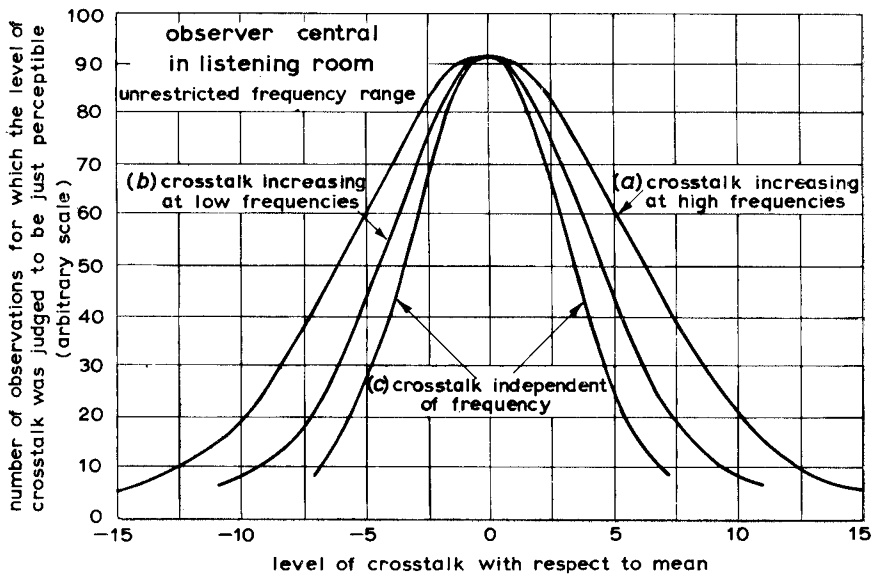

Fig. 12 - Distribution of levels given by team for minimum perceptible crosstalk. Observer central in Listening Room

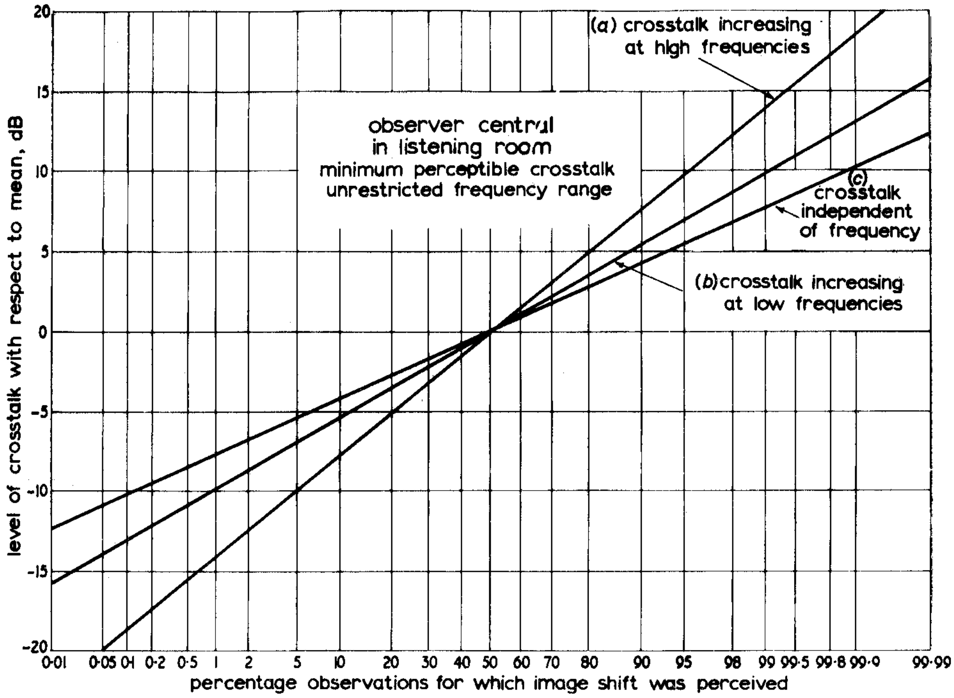

Fig. 13 - Distribution of levels given by team for minimum perceptible crosstalk. (Probability scale) Observer central in Listening Room

in Fig. 14 on a Gaussian probability scale showing the distribution of the values obtained. Although the data apply to a variety of experimental conditions - crosstalk increasing at low frequencies and at high frequencies respectively, with three different bandwidths in each case - all the points derived from dead room tests are found to lie nearly on one straight line and all the points derived from listening room tests on another. For the listening room, the mean value of the ordinate is 1·9° and for the dead room, 2·7°, a significant difference since the standard errors in the two cases are only 0·17° and 0·25° respectively. Thus, the observer's acuity, expressed in terms of image displacement, as distinct from the minimum perceptible crosstalk referred to in Section 3.1., was greater in the listening room than in the dead room. No explanation has so far been found for this effect, but it is conceivable that the first reflexion from the floor or ceiling of the listening room may contribute additional directional information to the ear.

3.5. Lateral bias of Observers

As already indicated in 2.1., every test carried out with the programme on the left channel and crosstalk on the right was repeated with the positions of the channels interchanged. Analysis of the differences between the results obtained in the two cases, together with evidence from additional tests carried out with the loudspeakers interchanged, failed to reveal any significant degree of asymmetry in the experimental arrangements. Most of the observers, however, were found to exhibit a left or right bias, being in some cases as much as 10 dB more sensitive to crosstalk

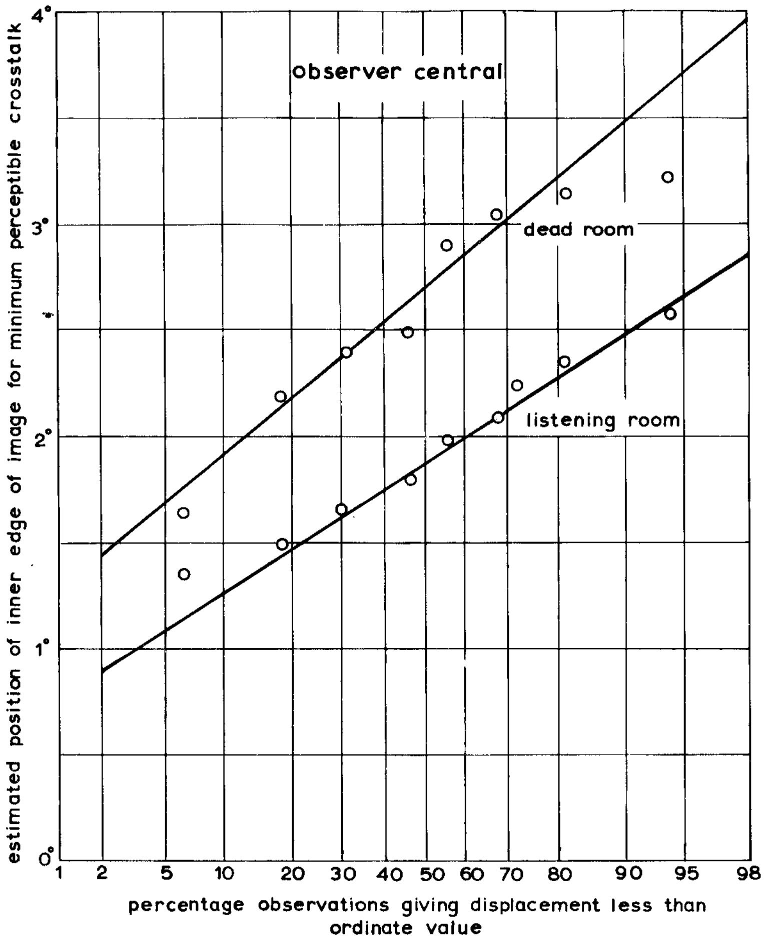

Fig. 14 - Distribution of values of displacement assigned to inner edge of image for minimum perceptible crosstalk. Observer central in Dead Room and Listening Room

from one side than from the other. Fig. 15 shows the mean bias for the team - taken without regard to sign - as a function of image displacement, for various experimental conditions; the values range from 2 dB to 4·6 dB, representing deviations of ± 1 dB to ± 2·3 dB about the crosstalk figure averaged for all the tests.

4. COMPARISON WITH EARLIER WORK

Little is to be found in the literature on the subject of interchannel crosstalk, and the only work of immediate interest for purposes of comparison appears in papers by Harvey and Schroeder of the Bell Telephone Laboratories[4] and McCoy of the R.C.A. Laboratories.[5]

Harvey and Schroeder employed a system of split-band filters so arranged that above or below a predetermined frequency the left- and right-hand channels were in effect connected in parallel; in the transition region, the channel separation changed, within half an octave, from less than 1 dB to greater than 20 dB. Tests were also carried out with crosstalk varying in amount but independent of frequency.

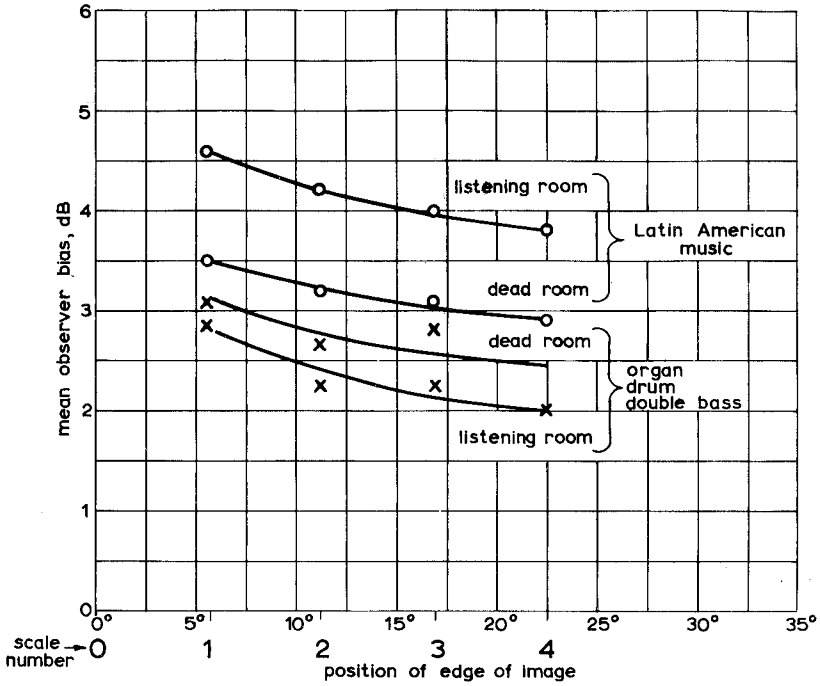

Fig. 15 - Left or Right Bias of individual observers as a function of image position. Observer central in Dead Room and Listening Room

The programme material consisted of stereophonic recordings and the assessment was based on the proportion of observers who noticed the impairment produced by the crosstalk. It was concluded that in setting commercial standards for stereophonic transmission, the crosstalk level should be at least 20 dB below the programme level for the frequency range 100 c/s to 8 kc/s. This limit of 20 dB agrees closely with the minimum perceptible crosstalk level shown in Fig. 7 for male speech. Apart from this, however, direct comparison between Harvey and Schroeder's results and those given in this report is not possible because the increase in crosstalk with frequency at the ends of the band was in the former case abrupt, but in the latter, gradual; moreover, an increase in the tolerable amount of crosstalk at low frequencies is to be expected when the phase of the crosstalk lags 90° with respect to that of the programme.

In McCoy's experiments, crosstalk was introduced at low and high frequencies respectively by temporarily converting the left- and right-hand stereophonic signals to the equivalent sum and difference signals and inserting a high- or low-pass filter in the difference channel; in some of the tests, the phase shift introduced by the filter in the pass band was compensated by an all-pass network inserted in the sum channel. The sum and difference signals were then added and subtracted, producing left- and right-hand signals together with crosstalk varying with frequency in a manner depending on the characteristics of the filter. As in the experiments described in this report, the incoming programme was applied to one channel only, thus producing an image whose intended position was on the extreme left or right of the stage, and the effect of the crosstalk was expressed in terms of lateral spread of the sound. In some of McCoy's tests, filters with a sharp cut-off were used and, as in the case of the Harvey and Schroeder experiments, the results cannot be directly

compared with those given in this report. In other tests, however, the filter consisted of a simple resistance-capacity network, so that the rate of change of crosstalk with frequency was more gradual and in these cases some comparisons can be made. The programme items in the two sets of experiments are also comparable, the pizzicato double-bass and Latin American music in this investigation having a rough parallel in the jazz band recording used by McCoy and described as 'strong strummed bass viol with celeste and other moderate level medium and high-frequency percussion'. In Fig. 16, curves (a) and (b) are computed from the data obtained by McCoy with a resistance-capacity filter, using phase compensation; in this case the crosstalk was in phase with the programme. Curve 16(a) applies to crosstalk increasing with frequency; it shows the crosstalk/frequency characteristic which in McCoy's experiments produced on average an image 'spread' of 1/10th stage width. Curve 16(b), obtained in a similar fashion, applies to crosstalk increasing at low frequencies. For comparison, the corresponding curves 16(c) and 16(d) are derived from the data already given in Figs. 3(a) and 5(a) respectively. It will be seen that curves (a) and (b) show a somewhat lower degree of crosstalk than curves (c) and (d) for the same degree of image displacement; in the low-frequency range, curves (b) and (d), some of this difference can be accounted for by the 90° phase lag referred to earlier.

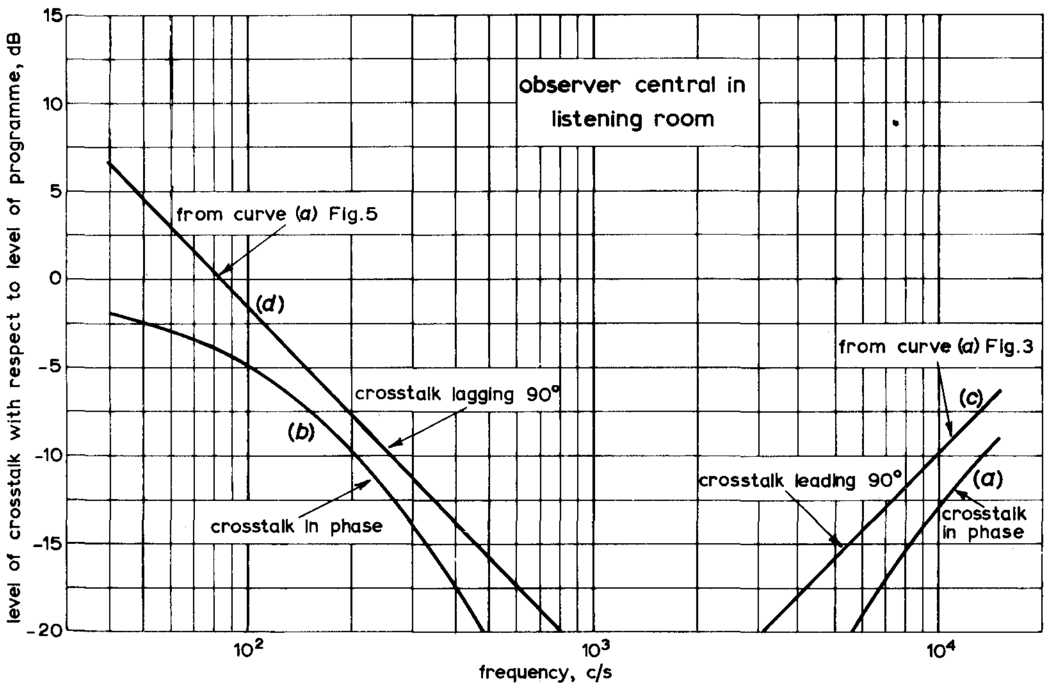

Fig. 16 - Crosstalk/frequency characteristics which produce, on average, an image spread of 1/10th stage width

(a) and (b) calculated from McCoy's data (1961)

(c) and (d) calculated from Figs. 3(a) and 5(a) respectively of present report

5. CONCLUSIONS

Data have been obtained on the impairment of a stereophonic image through various forms of interchannel crosstalk which may occur in practice. The minimum perceptible degree of crosstalk is influenced to some extent by the position of the observer in the listening room but is largely independent of the acoustics of the room and of the bandwidth of the system. For reasons not yet clear, the acuity of the observer's directional sense, as measured by the ability to repeat results, was greater in an acoustic environment similar to that of an average living room than in free space conditions.

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